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Short and Long Term Performance of Concrete Structures Repaired/Strengthened with FRP

by

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the requirements for the degree of
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Certificate of authorship/originality

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

Muhammad Ikramul Kabir

Date:

*To my parents because of whom I have found my existence in the vivid
and vibrant Earth*

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List of publications based on this thesis

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Abstract

Fibre Reinforced Polymer (FRP) composites have lately become a popular choice for strengthening and/or repairing of reinforced concrete (RC) structures due to their advantageous properties such as high strength- to-weight ratio, high corrosion resistance and easy application process. As the performance of FRP bonded RC structures depends on the effective stress transfer between FRP and concrete, extensive research has been conducted on the FRP-concrete bond system under short term loads. However, studies on the long term performance of FRP-concrete bond subjected to environmental conditions are very limited.

Experimental studies on the long term performance of FRP strengthened structures to-date include the study of the effect of various environmental conditions using a variety of test set-ups such as pull-off, bending tests of beams and direct shear tests. However, the available studies based on various conditions and set-ups make it difficult to compare the findings. As the effectiveness of FRP-strengthening schemes, either used for flexural or shear strengthening, lies in the shear stress transfer between FRP and concrete, study of FRP-concrete bond subjected to different environmental conditions by direct shear tests were suggested by some of the researchers. Even sensitivity of this set-up to environmental conditions was also reported. Therefore, more research with similar test set-ups to create a large database of FRP-concrete bond behaviour under various environmental conditions can be of immense value. In addition, using very high temperature for accelerated ageing was found to be very common in available literatures. However, in reality structures may not be exposed to such high temperatures and using high temperature may lead to conservative prediction of long-term properties. Moreover, unavailability of test data for FRP-concrete bond subjected to natural ageing observed in the existing literatures necessitates the investigation on FRP-concrete behaviour under natural environment.

In regards to the short term performance of reinforced concrete beams strengthened and/or repaired with FRP, extensive research have been conducted to-date in terms of experimental and analytical study. Some of these studies have also proposed design guidelines. However, the equations for prediction of load carrying capacity of severely

damaged repaired beams, especially, considering the strain hardening after yielding are not recommended.

Considering the identified gaps in the previous research on long term performance of FRP-concrete bond system and the short term performance of RC beams strengthened and/or repaired with FRP, the research study presented in this dissertation has mainly focused on the experimental investigation of the long-term performance of carbon FRP and glass FRP-concrete bond under three separate environmental conditions, namely, temperature cycles, wet-dry cycles and outdoor environment up to 18 months. The secondary objective is to investigate the effectiveness of typical FRP-strengthening schemes, used for strengthening of reinforced concrete beams, in the repair of severely damaged beams.

The long term performance of two types of FRP (CFRP and GFRP)-concrete bond is studied by extensive experimental investigations using single shear tests (is referred to as pull-out tests). The maximum temperature of the temperature cycles is intentionally kept below the glass transition temperature of epoxy resin to avoid any over-degradation. In the wet-dry cycles, temperature close to ambient is maintained. Also, outdoor environmental exposure is applied to address the unavailability of test data of natural ageing of FRP-concrete bond system. Pull-out tests conducted after exposure durations are analysed based on the pull-out strength, failure modes and strain distributions along the bond length. In addition, material properties, namely, CFRP tensile strength and modulus of elasticity, and concrete compressive strength are determined to understand the effect of changing material properties on the pull-out strength by correlation of bond strength with failure modes. Curve fitting of shear stresses against slips of only CFRP-concrete bond is conducted to determine the fracture energy release rate and the effect of environmental conditions on it. In addition, interface laws are proposed for control and exposed conditions based on an existing model. Results obtained for long term performance of bond systems provide interesting findings due to imposed environmental conditions. Based on the observations, strength reduction factors for CFRP and GFRP-concrete bond are proposed.

The short term performance of FRP-repaired beams is investigated both experimentally and analytically. Three severely damaged beams, fabricated from conventional concrete (normal concrete with water, cement and aggregate) and non-conventional concrete

(concrete with additives such as fibres and rubbers) are repaired with CFRP for flexure. Anchorage provided by complete CFRP wrapping at two ends and mid-span is found to be effective for preventing the debonding of FRP at least partially. Analytical study is conducted to understand the effect of existing steel reinforcement on the response of repaired beams under flexure. Considering the strain hardening of steel after yielding, equations are also proposed for better prediction of load carrying capacity of the repaired beams and compared with experimental results.

Finally, all the major findings of the two areas of research are summarised and recommendations for future research are made.

List of abbreviations and acronyms

ACI	American Concrete Institute
AFRP	Aramid Fibre Reinforced Polymer
AS	Australian Standard
ASTM	American Society for Testing and Materials
CF	Carbon Fibre
CFRP	Carbon Fibre Reinforced Polymer
CFS	Carbon Fibre Sheet
CoV	Coefficient of Variation
CSS	Carbon Strand Sheet
CZM	Cohesive Zone Model
DIC	Digital Image Correlation
DMTA	Dynamic Mechanical Thermal Analysis
EG	E-Glass
ERR	Energy Release Rate
FA	Fly Ash
FRP	Fibre Reinforced Polymer
GFRP	Glass Fibre Reinforced Polymer
GRC	Glass Fibre Reinforced Cement
IRRH	Interface Region Relative Humidity
IRT	Infrared Thermography
LED	Light Emitting Diode
LEFM	Linear Elastic Fracture Mechanics
LVDT	Linear Variable Differential Transformer
MOE	Modulus of Elasticity
NLFM	Nonlinear Fracture Mechanics
PC	Portland cement
PP	Polypropylene
QIRT	Quantitative Infrared Thermography
RC	Reinforced Concrete
RH	Relative Humidity
RTC	Residual Thickness of Concrete

List of abbreviations and acronyms

SBR	Styrene Butadiene Rubber
SCCB	Single Contoured Cantilever Beam
SG	Strain Gauge
TSF	Time Shift Factor
UV	Ultraviolet
VCCT	Virtual Crack Closure Technique

List of notations

A	A constant in the test condition for accelerated ageing with Arrhenius principle
A_f	Cross sectional area of FRP
a_f	Depth of equivalent rectangular stress block of FRP strengthened/repaired beam
$A_{f_{anchor}}$	Area of FRP anchor
A_s	Area of steel reinforcement
$A_{s_{bottom}}$	Area of bottom steel reinforcement
$A_{s_{top}}$	Area of top steel reinforcement
b	Width of beam
b_c	Width of a concrete member
b_f	Width of FRP plate or sheet
c	The depth of neutral axis of a beam / interface cohesion in a Mohr-Coulomb envelope
c_f	A regression constant for fracture energy
C_{th}	Threshold interface moisture content beyond which no further degradation occurs
d	Depth of bottom steel axis from the top of the beam
d'	Depth of top steel axis from the top of the beam
E_a	Activation energy
E_c	Elastic modulus of concrete
E_f	Tensile modulus of elasticity of FRP
E_s	Tensile modulus of elasticity of steel
f'_c	Concrete compressive strength
f_{ctm}	Concrete surface tensile strength
f_f	Axial stress in FRP plate or sheet
f_{fu}	Ultimate tensile stress in FRP at rupture

List of notations

$f_{s\text{ Res}}$	Residual strength of steel
f_t	Tensile strength of concrete
f_u	Ultimate tensile stress of steel
f_y	Yield stress of steel
G_f	Fracture energy/fracture energy release rate
G_{Ic}	Fracture energy under mode I loading
G_{IIc}	Fracture energy under mode II loading
h	Height of beam
J	Energy release rate at a debonding tip
k	Reaction rate constant with respect to a temperature T
k_f	Geometrical factor related to FRP width and concrete width
L_e	Effective bond length
M_n	Nominal moment capacity of beam
P_f	Applied load in FRP
P_{\max}	Ultimate bond strength / ultimate load at bond failure
R	Universal gas constant
s_{\max}	Slip value at the maximum shear stress
T	Absolute temperature in Kelvin
t	Time
t_f	Thickness of FRP sheet or plate
T_g	Glass transition temperature (sometimes referred to as heat distortion temperature) of polymer
w_f	Width of FRP anchor
Y	Tensile strength retention value
β_L	Length factor of FRP-concrete bond
β_p	Width factor of FRP-concrete bond
δ or s	Slip between FRP and concrete
δ_f	Maximum slip of FRP-concrete bond

List of notations

ε_f	Axial strain in FRP
ε_{f0}	Initial strain of concrete at the level of FRP reinforcement
$\varepsilon_{fe_{anchor}}$	Effective strain of FRP anchor
ε_{fu}	Ultimate tensile strain of FRP
ε_{s0}	Initial strain the steel reinforcement
ε_u	Ultimate tensile strain of steel
ε_y	Yield strain of steel
$\sigma(t)$ or $P(t)$	Composite strength after an exposure time t
σ_0 or P_0	Composite strength for unexposed condition
σ_∞	Composite strength after infinite exposure time
σ_{db}	Maximum axial stress of FRP at debonding failure
τ	Interface shear stress / a characteristic time dependent on temperature
τ_{max}	Maximum shear stress at failure of bond
ϕ	Friction angle in a Mohr-Coulomb envelope

Table of contents

Certificate of authorship/originality	i
Acknowledgments	iii
List of publications based on this thesis	v
Abstract	vi
List of abbreviations and acronyms	ix
List of notations	xi
Table of contents	xiv
List of tables	xxi
List of figures	xxv
1 Introduction	1
1.1 Preamble	1
1.2 Problem identification	2
1.2.1 Long term performance of FRP-concrete bond	2
1.2.2 Repairing of severely damaged reinforced concrete members with FRP ...	4
1.3 Research objectives	5
1.4 Significance of the research	6
1.5 Layout of the thesis	7
2 Literature review	10
2.1 Introduction	10
2.2 Fibre Reinforced Polymer (FRP) composites	10
2.2.1 Methods of forming FRP composites	11
2.2.2 Mechanical properties of FRP composites	12
2.3 Bond strength and bond strength models	14
2.4 Durability of FRP and FRP-concrete structures	26
2.5 Long term performance prediction for FRP and FRP-concrete structures	27

Table of contents

2.5.1	Arrhenius principle.....	27
2.5.2	Time-temperature-stress superposition principle.....	28
2.5.3	Existing long term durability prediction models.....	28
2.6	Experimental study on durability of FRP-concrete structures	32
2.7	Repairing of RC beams with FRP	54
2.8	Critical review	62
2.9	Conclusions	63
3	Experimental program.....	66
3.1	Introduction	66
3.2	Overview of experiments	66
3.3	Pull-out test of FRP-concrete bond specimens.....	66
3.3.1	Geometry of pull-out specimens	67
3.3.2	Fabrication of pull-out specimens and material properties	68
3.3.3	Exposure Conditions	73
3.3.3.1	Control specimens.....	73
3.3.3.2	Exposed specimens	73
3.3.4	Test set-up and instrumentation	79
3.3.5	Experimental procedure	81
3.4	Tensile test of FRP coupons	82
3.4.1	Geometry of FRP tensile coupons.....	82
3.4.2	Fabrication of FRP tensile coupons and material properties	83
3.4.3	Exposure conditions	84
3.4.4	Test set-up and instrumentation	86
3.4.5	Experimental procedure	87
3.5	Concrete compressive strength and static chord modulus of elasticity test	87
3.6	Results of Tensile testing of FRP	87
3.6.1	Tensile properties of FRP control coupons.....	88

Table of contents

3.6.1.1	CFRP tensile properties	88
3.6.1.2	GFRP tensile properties	90
3.6.2	Tensile properties of CFRP exposed coupons	92
3.6.2.1	Temperature cycles	92
3.6.2.2	Wet-dry cycles	94
3.6.2.3	Outdoor environment	95
3.7	Results of compressive testing of concrete	96
3.7.1	Control cylinders	96
3.7.2	Exposed cylinders	96
3.7.2.1	Temperature cycles	97
3.7.2.2	Wet-dry cycles	98
3.7.2.3	Outdoor environment	98
3.8	Test results of control pull-out specimens	99
3.8.1	CFRP control specimens	100
3.8.1.1	Pull-out strengths	100
3.8.1.2	Failure modes	101
3.8.1.3	Strain profiles	103
3.8.2	GFRP control specimens	108
3.8.2.1	Pull-out strength	108
3.8.2.2	Failure modes	108
3.8.2.3	Strain profiles	109
3.9	Chapter summary	112
4	Effect of cyclic temperature on FRP-concrete bond	115
4.1	Introduction	115
4.2	Test results of CFRP cyclic temperature series	115
4.2.1	Pull-out strength	115
4.2.2	Failure modes	117

Table of contents

4.2.3	Strain profiles	119
4.2.4	Discussion of test results	125
4.3	Test results of GFRP temperature series	125
4.3.1	Pull-out strength	125
4.3.2	Failure modes	127
4.3.3	Strain profiles	129
4.3.4	Discussion of test results	133
4.4	Chapter summary	134
5	Effect of wet-dry cycles on FRP-concrete bond	136
5.1	Introduction	136
5.2	Test results of CFRP wet-dry series	136
5.2.1	Pull-out strength	136
5.2.2	Failure modes	139
5.2.3	Strain profiles	141
5.2.4	Discussion of test results	150
5.3	Test results of GFRP wet-dry series	151
5.3.1	Pull-out strength	151
5.3.2	Failure modes	153
5.3.3	Strain profiles	155
5.3.4	Discussion of test results	164
5.4	Chapter summary	164
6	Effect of outdoor environment on FRP-concrete bond	167
6.1	Introduction	167
6.2	Test results of CFRP outdoor environment series	167
6.2.1	Pull-out strength	167
6.2.2	Failure modes	170
6.2.3	Strain profiles	172

Table of contents

6.2.4	Discussion of test results	180
6.3	Test results of GFRP outdoor environment series	181
6.3.1	Pull-out strength	181
6.3.2	Failure modes	184
6.3.3	Strain profiles	185
6.3.4	Discussion of test results	194
6.4	Chapter summary	194
7	Study on the fracture properties of CFRP-concrete bond exposed to three environmental conditions	197
7.1	Introduction	197
7.2	Determination of shear stress-slip relationship and fracture energy	198
7.2.1	Shear stress and slip from strains along CFRP bond length	198
7.2.2	Determination of Fracture energy release rate	201
7.3	Results and discussions	203
7.3.1	Fracture properties of control specimens	203
7.3.2	Fracture properties of exposed specimens	208
7.3.2.1	Cyclic temperature series	209
7.3.2.2	Wet-dry series	216
7.3.2.3	Outdoor environment series	223
7.4	Proposed interface laws	230
7.4.1	Interface law for control series	230
7.4.2	Interface laws for exposed series	231
7.4.2.1	Cyclic temperature series	231
7.4.2.2	Wet-dry series	231
7.4.2.3	Wet-dry series	232
7.5	Chapter summary	232

Table of contents

8	Experimental study on short term performance of reinforced concrete structures repaired with FRP	236
8.1	Introduction	236
8.2	Experimental investigation.....	237
8.2.1	Fabrication of beams and geometric properties	237
8.2.2	Repair scheme for damaged beams.....	238
8.2.3	Design of repair scheme.....	242
8.2.4	Four-point-bending test.....	244
8.3	Test results and discussion	245
8.3.1	Load-deflection response	245
8.3.2	Failure modes	248
8.3.3	Strain profiles	249
8.3.4	Comparison of experimental with analytical results.....	252
8.4	Analytical study on the effect of steel reinforcement on the performance of repaired beams	253
8.4.1	Results of the analytical study on the effect of steel reinforcement	257
8.4.2	Prediction of load-carrying capacity of repaired beams considering steel strain hardening.....	260
8.5	Conclusions	263
9	Conclusions and recommendations for future research	266
9.1	Introduction	266
9.2	Material properties due to exposure	267
9.3	Long term performance of FRP-concrete bond.....	268
9.4	Strength reduction factors for long term performance of FRP-concrete bond	271
9.5	Short term performance of CFRP repaired beams	273
9.6	Recommendations for future research.....	273

References	276
A. Appendix A: Material test results for long term performance of FRP-concrete bond	
287	
A.1 Concrete compressive strength.....	287
A.2 Tensile stress-strain curves of FRP coupons	289
A.3 Tensile strength and modulus of elasticity (MOE) of FRP	301
A.4 FRP failure modes	307
A.5 Material data sheets for FRP	313
B. Appendix B: Pull-out test results	317
B.1 Failure modes of CFRP pull-out specimens.....	317
B.2 Failure modes of GFRP pull-out specimens.....	319
C. Appendix C: Fracture properties of CFRP-concrete bond.....	324
C.1 Shear stress-slip curve fitting for individual control specimens	324
C.2 Shear stress-slip curve fitting for control and exposed specimens with a single curve for each series.....	329
D. Appendix D: Short term performance of FRP-repaired beams.....	331
D.1 Prediction of load-carrying capacity of repaired beams considering strain hardening and residual strength of steel.....	331
D.2 Material data sheets	332

List of tables

Table 2.1 Typical mechanical properties of CFRP, GFRP and AFRP composites (Head 1996)	13
Table 2.2 Environmental conditions used by Grace (2004).....	39
Table 2.3 Environmental conditions applied by Cromwell, Harries & Shahrooz (2011)	49
Table 3.1 Material properties of two batches of concrete	69
Table 3.2 Material properties of FRP.....	71
Table 3.3 Material properties of epoxy resin	72
Table 3.4 Number of pull-out specimens	78
Table 3.5 Number of FRP tensile coupons exposed to environmental conditions	85
Table 3.6 Tensile properties of CFRP control coupons	89
Table 3.7 Tensile properties of GFRP control coupons.....	91
Table 3.8 Compressive properties of control concrete cylinders.....	96
Table 3.9 Pull-out strengths of control CFRP specimens from concrete batch 1	100
Table 3.10 Pull-out strengths of control CFRP specimens from concrete batch 2	101
Table 3.11 Pull-out strengths of control GFRP specimens	109
Table 4.1 CFRP Pull-out strengths of cyclic temperature specimens.....	117
Table 4.2 GFRP Pull-out strengths of cyclic temperature specimens.....	126
Table 5.1 CFRP Pull-out strengths of wet-dry specimens	138
Table 5.2 GFRP pull-out strengths of wet-dry specimens	152
Table 6.1 CFRP pull-out strengths of outdoor environment specimens from batch 1..	168
Table 6.2 CFRP pull-out strengths of outdoor environment specimens from batch 2..	169
Table 6.3 Pull-out strengths of GFRP outdoor environment specimens.....	183
Table 7.1 Shear stress-slips and fracture energies of Control specimens	206

List of tables

Table 7.2 Shear stress-slips and fracture energies of Control specimens from concrete batch 2	208
Table 7.3 Shear stress-slips and fracture energies of cyclic temperature specimens	212
Table 7.4 Shear stress-slips and fracture energies of wet-dry specimens	220
Table 7.5 Shear stress-slips and fracture energies for outdoor environment specimens	228
Table 8.1 Material properties of control beams	238
Table 8.2 Material properties of CFRP, epoxy resin and high build repair mortar	241
Table 8.3 FRP reinforcement details.....	242
Table 8.4 Strength and deflection properties of control and repaired beams.....	248
Table 8.5 Analytical and experimental load carrying capacity of repaired beams	253
Table 8.6 Analytical and experimental load carrying capacity of repaired beams considering the residual steel strength	263
Table 9.1 Strength reduction factors for CFRP and GFRP-concrete bond.....	272
Table A.1 Compressive strength of concrete for CFRP cyclic temperature pull-out specimens	287
Table A.2 Compressive strength of concrete for GFRP cyclic temperature pull-out specimens	287
Table A.3 Compressive strength of concrete for CFRP cyclic wet-dry pull-out specimens	288
Table A.4 Compressive strength of concrete for GFRP cyclic wet-dry pull-out specimens	288
Table A.5 Compressive strength of concrete for CFRP outdoor environment pull-out specimens	288
Table A.6 Compressive strength of concrete for GFRP outdoor environment pull-out specimens	289
Table A.7 Tensile properties of CFRP five week cyclic temperature coupons	301
Table A.8 Tensile properties of CFRP three month cyclic temperature coupons.....	302

List of tables

Table A.9 Tensile properties of CFRP one year cyclic temperature coupons	302
Table A.10 Tensile properties of CFRP one month cyclic wet-dry coupons.....	303
Table A.11 Tensile properties of CFRP six month cyclic wet-dry coupons.....	303
Table A.12 Tensile properties of CFRP one year cyclic wet-dry coupons.....	304
Table A.13 Tensile properties of CFRP 18 month cyclic wet-dry coupons	304
Table A.14 Tensile properties of CFRP two month outdoor environment coupons.....	305
Table A.15 Tensile properties of CFRP six month outdoor environment coupons	305
Table A.16 Tensile properties of CFRP one year outdoor environment coupons	306
Table A.17 Tensile properties of CFRP 18 month outdoor environment coupons.....	306
Table C.1 Fitting parameters for rational fits of control specimens	325
Table C.2 Fitting parameters for Dai, Ueda & Sato (2005) model fits for control specimens	326
Table C.3 Fitting parameters for rational fits for control specimens from concrete batch 2.....	327
Table C.4 Fitting parameters for Dai, Ueda & Sato (2005) model fits for control specimens from concrete batch 2	328
Table C.5 Fitting parameters for rational fits for control series.....	329
Table C.6 Fitting parameters for Dai, Ueda & Sato (2005) model fits for control series	329
Table C.7 Fitting parameters for rational fits for cyclic temperature series	329
Table C.8 Fitting parameters for Dai, Ueda & Sato (2005) model fits for cyclic temperature series.....	329
Table C.9 Fitting parameters for rational fits for cyclic wet-dry series	330
Table C.10 Fitting parameters for Dai, Ueda & Sato (2005) model fits for cyclic wet-dry series.....	330
Table C.11 Fitting parameters for rational fits for outdoor environment series	330

Table C.12 Fitting parameters for Dai, Ueda & Sato (2005) model fits for outdoor environment series	330
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List of figures

Figure 2.1 Cross section of a FRP sheet formed by wet lay-up process (taken from Shrestha (2009))	11
Figure 2.2 Typical FRP and mild steel tensile stress-strain curves (Teng 2002).....	13
Figure 2.3 Triangular shear-slip model.....	17
Figure 2.4 Shear slip model (adopted from Chen & Teng (2001)).....	25
Figure 2.5 Test Set-up (Chajes, Thomson & Farschman 1995).....	33
Figure 2.6 FRP bonded concrete prism (Homam, Sheikh & Mukherjee 2001).....	36
Figure 2.7 Freeze-thaw cycling scheme (Boyajian, Ray & Davalos 2007)	40
Figure 2.8 Relation between normalised RTC and IRRH (Ouyang & Wan 2008a).....	41
Figure 2.9 Specimen geometry for four point bending test by Silva and Biscaia (2008)	43
Figure 2.10 Shear tests for characterisation of Mohr-Coulomb Silva & Biscaia (2010)	48
Figure 2.11 (a) Specimen dimensions and (b) test set-up Yun and Wu (2011).....	50
Figure 2.12 (a) Peel and (b) shear fracture specimens (Tuakta & Büyüköztürk 2011b)	53
Figure 2.13 (a) Peel and (b) shear test set-ups (Tuakta & Büyüköztürk 2011b)	54
Figure 2.14 Idealised stress-strain curve for concrete in uni-axial compression (An, Saadatmanesh & Ehsani 1991).....	56
Figure 2.15 Stress-strain diagram for concrete and stress block assumption (Picard, Massicotte & Boucher 1995)	57
Figure 2.16 Flexural strengthening of RC beams (Teng 2002)	61
Figure 2.17 Typical wrapping schemes for shear strengthening of beams (ACI 440.2R 2008)	61

List of figures

Figure 3.1 (a) Plan and (b) elevation of pull-out specimen	68
Figure 3.2 (a) Concrete substrate preparation and (b) air blow-gun	70
Figure 3.3 (a) Carbon fibre and (b) glass fibre sheets.....	71
Figure 3.4 (a) Application of epoxy, (b) bonding FRP to concrete, (c) saturation of fibres with a roller and (d) fabricated pull-out specimen under curing.....	72
Figure 3.5 (a) Specimens in drying oven and (b) temperature cycles.....	74
Figure 3.6 (a) Humidity chamber and (b) temperature and humidity data-logger.....	75
Figure 3.7 Wet-dry cycles with corresponding temperature	75
Figure 3.8 Specimens under outdoor environmental exposure.....	76
Figure 3.9 Three environmental parameters for outdoor environmental exposure <i>Source: Australian Government Bureau of Meteorology</i>	77
Figure 3.10 Pull-out test set-up: (a) schematic diagram and (b) photograph.....	80
Figure 3.11 (a) Data taker, (b) BCM Strain gauge, (c) jaws used for gripping and (d) LVDT	80
Figure 3.12 Strain gauge locations.....	81
Figure 3.13 (a) Plan and (b) elevation of FRP tensile coupon	83
Figure 3.14 (a) FRP application on mould and (b) curing of FRP in lab condition.....	84
Figure 3.15 Test set-up of tensile testing of FRP coupon	86
Figure 3.16 Typical tensile stress-strain curve of CFRP control specimens.....	88
Figure 3.17 Failed CFRP tensile control coupons	90
Figure 3.18 Stress-strain curve of GTControl-2	91
Figure 3.19 Failed GFRP control coupons.....	92
Figure 3.20 Normalised tensile strengths and MOEs of CFRP cyclic temperature series with exposure duration.....	93
Figure 3.21 Normalised tensile strengths and MOEs of CFRP wet-dry series with exposure duration	94

List of figures

Figure 3.22 Normalised tensile strengths and MOEs of CFRP outdoor environment series with exposure duration.....	95
Figure 3.23 Normalised compressive strengths of concrete exposed to cyclic temperature against exposure duration.....	97
Figure 3.24 Normalised compressive strengths of concrete exposed to wet-dry cycles with exposure duration.....	98
Figure 3.25 Normalised compressive strengths of concrete exposed to outdoor environment with exposure duration.....	99
Figure 3.26 Failure modes of control CFRP pull-out specimens.....	102
Figure 3.27 Failure modes of control CFRP pull-out specimens from batch 2	103
Figure 3.28 Typical strain gauge locations	105
Figure 3.29 Strain profiles of control CFRP pull-out specimens.....	106
Figure 3.30 Strain profiles of CFRP control pull-out specimens from concrete batch 2	108
Figure 3.31 Failure modes of Control GFRP pull-out specimens.....	109
Figure 3.32 Strain profiles of GFRP control pull-out specimens	111
Figure 4.1 Normalised pull-out strength of CFRP cyclic temperature series against exposure duration.....	116
Figure 4.2 Failure modes of CFRP cyclic temperature specimens	119
Figure 4.3 Strain gauge locations.....	120
Figure 4.4 Strain profiles of five week CFRP temperature series.....	122
Figure 4.5 Strain profiles of three month CFRP temperature series	123
Figure 4.6 Strain profiles of one year CFRP temperature series.....	124
Figure 4.7 Normalised pull-out strength of GFRP cyclic temperature series against exposure duration.....	127
Figure 4.8 Failure modes of GFRP cyclic temperature specimens	128
Figure 4.9 Strain profiles of five week GFRP temperature series	130

List of figures

Figure 4.10 Strain profiles of three month GFRP temperature series.....	131
Figure 4.11 Strain profiles of GFRP one year temperature series	133
Figure 5.1 Normalised pull-out strength of CFRP wet-dry series against exposure duration	137
Figure 5.2 Failure modes of CFRP wet-dry specimens	140
Figure 5.3 Strain gauge locations.....	142
Figure 5.4 Strain profiles of CFRP one month wet-dry series.....	144
Figure 5.5 Strain profiles of CFRP six month wet-dry series	146
Figure 5.6 Strain profiles of CFRP one year wet-dry series	148
Figure 5.7 Strain profiles of CFRP 18 month wet-dry series.....	149
Figure 5.8 Normalised pull-out strength of GFRP wet-dry series with exposure duration	153
Figure 5.9 Failure modes of GFRP wet-dry specimens	155
Figure 5.10 Strain profiles of GFRP one month wet-dry series.....	157
Figure 5.11 Strain profiles of GFRP six month wet-dry series.....	159
Figure 5.12 Strain profiles of GFRP one year wet-dry series	161
Figure 5.13 Strain profiles of GFRP 18 month wet-dry series	163
Figure 6.1 Normalised pull-out strengths of CFRP outdoor environment series with exposure duration	170
Figure 6.2 Failure modes of CFRP outdoor environment specimens	172
Figure 6.3 Strain gauge locations.....	173
Figure 6.4 Strain profiles of CFRP two month outdoor environment series	174
Figure 6.5 Strain profiles of CFRP six month outdoor environment series.....	176
Figure 6.6 Strain profiles of CFRP one year outdoor environment series	178
Figure 6.7 Strain profiles of CFRP 18 month outdoor environment series	180
Figure 6.8 Normalised pull-out strengths of GFRP outdoor environment series with exposure duration	182

List of figures

Figure 6.9 Failure modes of GFRP outdoor environment specimens	185
Figure 6.10 Strain profiles of GFRP two month outdoor environment series	187
Figure 6.11 Strain profiles of GFRP six month outdoor environment series.....	189
Figure 6.12 Strain profiles of GFRP one year outdoor environment series.....	191
Figure 6.13 Strain profiles of GFRP 18 month outdoor environment series	193
Figure 7.1 Pull-out test set-up (Dai, Ueda & Sato 2005)	199
Figure 7.2 Strain gauges used for slip measurements	201
Figure 7.3 Fitted curves for CControl-1.....	204
Figure 7.4 fitted curves for CControl series.....	205
Figure 7.5 Fitted curves for CControl-2 (B2)	207
Figure 7.6 Fitted curves for CControl (B2) series.....	208
Figure 7.7 Fitted curves for CT2 series.....	210
Figure 7.8 Fitted curves for CT3 series.....	211
Figure 7.9 Fitted curves for CT4 series.....	212
Figure 7.10 Normalised maximum shear stress against days of exposure for cyclic temperature specimens	213
Figure 7.11 Normalised fracture energy against days of exposure for cyclic temperature specimens	214
Figure 7.12 Fitted curves for CH1 series	217
Figure 7.13 Fitted curves for CH2 series	218
Figure 7.14 Fitted curves for CH3 series	219
Figure 7.15 Fitted curves for CH4 series	220
Figure 7.16 Normalised maximum shear stress against days of exposure for wet-dry specimens	221
Figure 7.17 Normalised fracture energy against days of exposure for wet-dry specimens	222
Figure 7.18 Fitted curves for CE1	224

List of figures

Figure 7.19 Fitted curves for CE2.....	225
Figure 7.20 Fitted curves for CE3.....	226
Figure 7.21 Fitted curves for CE4 series.....	227
Figure 7.22 Normalised maximum shear stress against days of exposure for outdoor environment specimens.....	228
Figure 7.23 Normalised fracture energy against days of exposure for outdoor environment specimens.....	229
Figure 8.1 Beam geometry and reinforcement details (Ghosni 2012).....	237
Figure 8.2 Repair scheme for the beams.....	239
Figure 8.3 Steps involved in beam repairing	240
Figure 8.4 Four-point-bending test set-up.....	245
Figure 8.5 Load-deflection plot of control and repaired beams.....	247
Figure 8.6 Failed repaired beams.....	249
Figure 8.7 Strain profiles of repaired beams.....	252
Figure 8.8 Schematic diagram of transformed cracked section of repaired beam	254
Figure 8.9 Load-deflection plot of Repaired Beam 1 considering the effects of steel reinforcement	258
Figure 8.10 Load-deflection plot of Repaired Beam 2 considering the effects of steel reinforcement	259
Figure 8.11 Load-deflection plot of Repaired Beam 3 considering the effects of steel reinforcements.....	260
Figure 8.12 Stress-strain curve of mild steel (Quantrill, Hollaway & Thorne 1996) ..	262
Figure A.1 Stress-strain curves of CFRP control coupons	290
Figure A.2 Stress-strain curves of GFRP control coupons	290
Figure A.3 Stress-strain curves of CFRP five week cyclic temperature coupons	291
Figure A.4 Stress-strain curves of CFRP three month cyclic temperature coupons.....	292
Figure A.5 Stress-strain curves of CFRP one year cyclic temperature coupons	293

List of figures

Figure A.6 Stress-strain curves of CFRP one month cyclic wet-dry coupons.....	294
Figure A.7 Stress-strain curves of CFRP six month cyclic wet-dry coupons.....	295
Figure A.8 Stress-strain curves of CFRP one year cyclic wet-dry coupons	296
Figure A.9 Stress-strain curves of CFRP 18 month cyclic wet-dry coupons.....	297
Figure A.10 Stress-strain curves of CFRP two month outdoor environment coupons .	298
Figure A.11 Stress-strain curves of CFRP six month outdoor environment coupons ..	299
Figure A.12 Stress-strain curves of CFRP one year outdoor environment coupons	300
Figure A.13 Stress-strain curves of CFRP 18 month outdoor environment coupons...	301
Figure A.14 Failed coupons of CFRP five week cyclic temperature series	307
Figure A.15 Failed coupons of CFRP three month cyclic temperature series	307
Figure A.16 Failed coupons of CFRP one year cyclic temperature series	308
Figure A.17 Failed coupons of CFRP one month cyclic wet-dry series.....	308
Figure A.18 Failed coupons of CFRP six month cyclic wet-dry series.....	309
Figure A.19 Failed coupons of CFRP one year cyclic wet-dry series	309
Figure A.20 Failed coupons of CFRP 18 month cyclic wet-dry series.....	310
Figure A.21 Failed coupons of CFRP two month outdoor environment series	310
Figure A.22 Failed coupons of CFRP six month outdoor environment series	311
Figure A.23 Failed coupons of CFRP one year outdoor environment series.....	311
Figure A.24 Failed coupons of CFRP 18 month outdoor environment series	312
Figure A.25 Material data sheet for MBRACE carbon and glass fibre	314
Figure A.26 Material data sheet for Sikadur 330 epoxy resin	316
Figure B.1 Failure modes of CFRP cyclic temperature pull-out specimens.....	317
Figure B.2 Failure modes of CFRP cyclic wet-dry pull-out specimens	318
Figure B.3 Failure modes of CFRP outdoor environment pull-out specimens.....	319
Figure B.4 Failure modes of GFRP control pull-out specimens.....	320
Figure B.5 Failure modes of GFRP cyclic temperature pull-out specimens.....	320

List of figures

Figure B.6 Failure modes of GFRP cyclic wet-dry pull-out specimens	321
Figure B.7 Failure modes of GFRP outdoor environment pull-out specimens.....	323
Figure C.1 Rational fits of control specimens.....	325
Figure C.2 Dai, Ueda & Sato (2005) model fits for control specimens.....	326
Figure C.3 Rational fits for control specimens from concrete batch 2	327
Figure C.4 Dai, Ueda & Sato (2005) model fits for control specimens from concrete batch 2	328
Figure D.1 Data sheets for repair mortar Sika Mono Top-615HB	336